techcommentary

Power Quality for Induction Melting in Metals Production

Introduction

Fast, efficient batch melting using the modern induction furnace can improve operating flexibility and production yield, as well as reduce the cost of environmental protection. The compelling advantages of induction batch melting have encouraged foundries to change the way they handle their melting operations. Among the chief advantages is cost. The operational cost of a typical induction-melt furnace is in the neighborhood of $130 per ton for steel, which compares favorably with the operational cost of a typical electric arc furnace.

Since the 1970s, induction has been the number one method of melting in non-ferrous metal foundries and an important tool in iron foundries. New technology is improving induction power supplies, furnace refractory linings, heat recovery, and overall system control. In the last ten years, the use of induction melting has increased by as much as 20% per year, making it the fastest growing electric technology in metals production. Over time, induction may even surpass conventional use of electric arc furnaces in both tons of production and kilowatt-hours of energy use.

Only a fraction the size of an electric arc furnace, the induction-melt furnace may still cause power quality problems in the electric utility system. Power quality problems are more likely when an induction-melt furnace is connected at distribution-level voltages, where the furnace current is relatively large compared to the utility supply. In a few cases, new installations of medium-frequency induction-melt furnaces have lead to difficult-to-resolve power interface problems. This *TechCommentary* is

Figure 1. Modern variable-frequency induction enables efficient batch-melting processes. The furnace is poured empty after each melt, and successive melts are started using unheated or preheated metal. Because there is no need to maintain a molten heel, smaller furnaces can be used, electrical energy goes further, alloy changes are easier, and loading safety is enhanced. Induction batch melting has brought about meaningful increases in both the efficiency and productivity of the modern melt shop.

intended to help both furnace users and their energy providers better anticipate and resolve power quality problems related to induction melting.

Electrical Characteristics of Induction Furnaces

The growth in use of induction melting has come about primarily because of significant technology advances in the furnace power supply and its resonant circuit. This growth is primarily in medium-frequency systems, sized from 0.2 to 16 MW and operating at frequencies from 150 to 3000 Hz. These medium-frequency furnaces have proven to be versatile and efficient at a relatively large scale. The older low-frequency models, which connect directly to the 60-Hz utility source, cannot

compete because of control and efficiency limitations. High-frequency systems, which operate at greater than 3 kHz, are relatively small and limited to special applications.

Despite the appeal of the medium-frequency induction furnace, the same advances that make it so effective also engender problems with the power interface. For example, consider harmonic distortion. Today, the most efficient furnaces run at full power and vary the frequency to optimize the melt. The furnace generates fixed- and variable-frequency harmonics that may lead to adverse interactions between the furnace and the utility system. This is particularly true of the popular high-power-density coreless-induction furnaces, which typically operate as a relatively large load at distribution-level voltage.

The Furnace Circuit

Electrically, an induction-melt furnace is simply a loosely coupled transformer. As shown in Figure 2, current in the power coil surrounding a ceramic crucible generates a magnetic field. Laminated iron
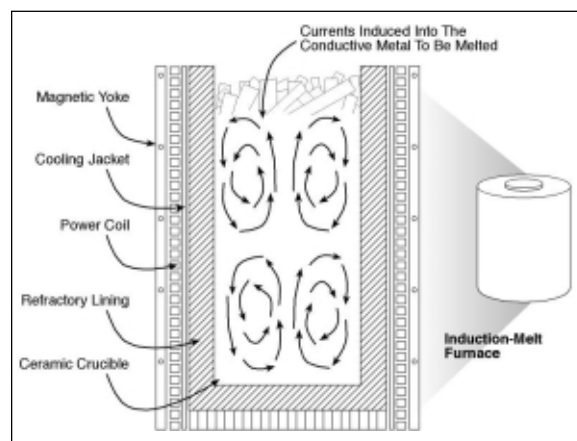

Figure 2. Components of a Large Induction-Melt Furnace

forms a magnetic yoke that also surrounds the crucible. The crucible helps to distribute and contain the field, which induces current in the conductive metal to be melted. The current that penetrates the metal is controlled to ensure proper stirring of the metal and prevent over-stirring. A concentrated current on the outer layer of metal to be melted generates the melting power as it quickly heats to the melting point. The refractory lining and cooling jacket separate the hot metal from the furnace power coil.

The power supply of an induction-melt furnace provides both the power and control required to properly melt metal. Early induction melting was carried out at line frequency, with power provided by a special transformer and tuning circuits. Switching capacitors provided power-factor adjustment, and changing transformer taps regulated the power level. For maximum melting power, the resonant frequency of a tuned LC circuit had to be matched to the line frequency. This condition limited the coil current and therefore the efficiency of the furnace because the 60-Hz line frequency results in relatively high penetration into the melt and excessive stirring. Also, early induction-melt furnaces were single-phase loads, which draw heavily from only one phase of a three-phase system and limit the power available from the utility service.

The advent of large-scale solid-state power supplies has greatly improved induction melting. Three-phase converters, can be operated at a high power factor, thereby increasing the practical power ratings in a typical application. These power supplies also precisely control frequency and the depth of penetration to efficiently melt the material without over-stirring. The process is more efficient because the variable-frequency power supplies are able to match the varying electrical characteristics of different metals during melting. The electronic power supply that is used on the modern furnace has opened the way for batch operation by eliminating the need to maintain a molten heel. Figure 3 shows a typical furnace and its electronic power supply.

To achieve an efficient and fast melt, more power per unit weight of the metal being melted is desired. Typical power densities in the medium-frequency furnace range
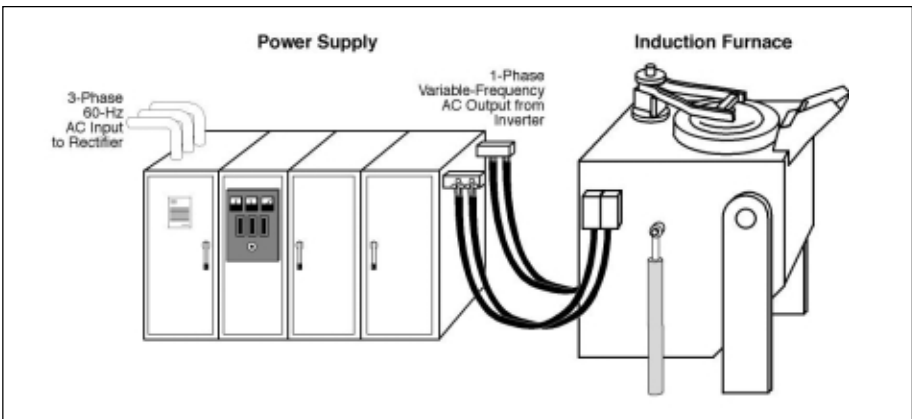

Figure 3. Typical Electronic Power Supply and Medium-Frequency Induction-Melt Furnace

from 600 to 1000 kW per ton, compared to 200 to 400 kW per ton in the line-frequency furnace. Electric arc furnaces also operate at high power densities. However, the arc melting temperatures are significantly higher than induction melting-in the neighborhood of 6000°F (3300°C), compared to 2600°F (1400°) for induction-melt furnaces. The higher temperature in an electric arc furnace enables the melting of somewhat dirtier metal but also leads to a few percent higher losses of metal to ionization and creation of ash.

Figure 4 illustrates recorded electrical parameters of an actual medium-frequency furnace during a typical batch cycle.

1. Metal is loaded into the furnace using a heavy duty conveyor. The melting process forms a molten bath in the bottom of the ceramic crucible. In this case loading continues until the crucible is filled with 10 tons (9 Mg) of molten metal, at about 2600°F (1400°C).

2. After all of the metal has melted, the batch is superheated to the desired tap temperature of about 2800°F (1500°C).

3. Then, the power is removed so that the molten metal can be poured into a ladle.

Depending on the relative size and configuration, furnace operation can affect power quality at the point of common coupling (PCC) or at the interface with the public power supply. Many different electronic power supply configurations are available. The choice of configuration will have a big impact on both furnace performance and electrical compatibility. The following is a summary of practical power supply options that may help to avoid costly corrective actions or operating curtailments when they are considered before furnace installation.

The Electronic Power Supply Circuit

Electronic power supplies control current and frequency for efficient induction melting. Most electronic power supplies
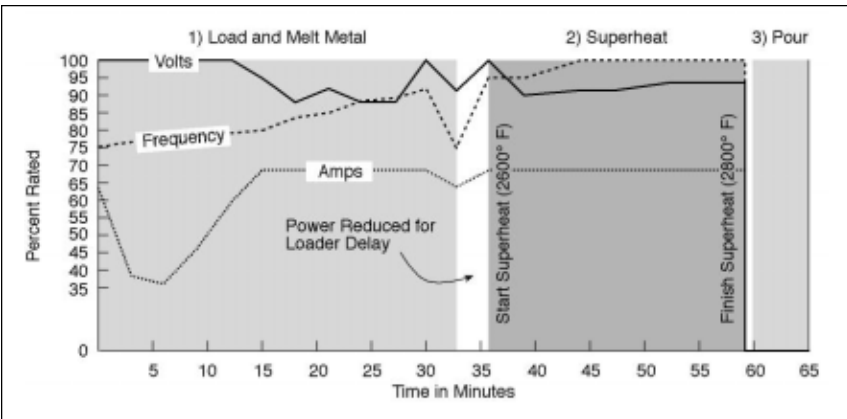

Figure 4. Electrical Parameters During a Typical Batch Cycle for a 6-MW, 2400-Volt Furnace (scrap iron loaded at 10 tons/hour (9 Mg/h); power supply running at 200 to 275 Hz, 36,000 Amps)

rectify the AC line current to provide a DC source of energy. This DC is then inverted at a frequency to obtain the desired induction from the furnace resonant circuit. The two main types of solid-state power supplies are the current-fed power supply (parallel furnace resonant circuit) and the voltage-fed power supply (series furnace resonant circuit), both of which are used in medium-frequency induction melting systems. These different power supply designs have different impacts on the furnace performance, as indicated in Table 1.

Voltage-Fed Power Supplies

The voltage-fed power supply, which is the newer of the two designs, takes advantage of switching technology that is capable of handling high currents. As shown in Figure 5, it employs a simple input diode rectifier to produce DC, and a parallel-connected DC capacitor for energy storage and filtering. The output inverter controls melting power by its commutation frequency and can fully regulate the current to the series tuning capacitor and the furnace. Consequently, the inverter is exposed to the full current and partial voltage of the furnace. The DC capacitor provides or absorbs excess energy for starting and stopping the inverter.

Current-Fed Power Supplies

As shown in Figure 6, the basic current-fed converter uses a phase-controlled rectifier to convert AC to DC and to regulate the voltage on the DC link. When current is flowing in the DC link, the two series-connected inductors provide energy storage and filtering. Consequently, a starter circuit is needed to energize these inductors, and a crowbar circuit is used to discharge them when the melt is complete. The inverter commutates or reverses the current to obtain the desired output frequency, which, along with varying the rectifier output voltage, controls the melting power.

Current-fed designs have been around longer and take advantage of rugged and economical switching-device technology. The inverter is exposed to the full furnace voltage. However, it only sees about 10% of the furnace resonant current because the reactive component of the furnace current bypasses the inverter via the parallel tuning capacitor. Consequently, the current-fed power supply has less control over the

Table 1. Performance and Interface Comparisons for Medium-Frequency Melt Furnaces

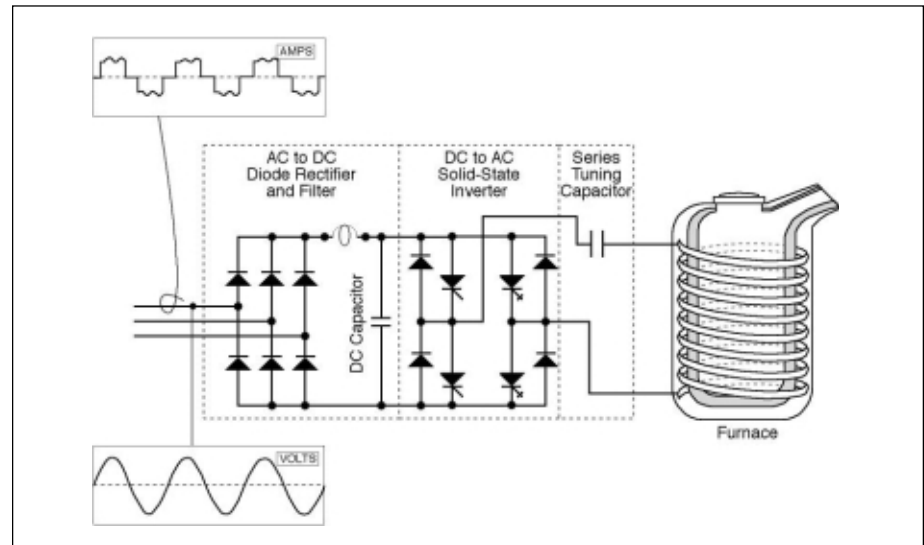| Characteristics	Current-Fed Inverter	Voltage-Fed Inverter
Controllability of Melt	Poor	Excellent
Efficiency of Melt	70-80%	75-85%
Power-Line Interface	Phase-Controlled Rectifier	Diode Rectifier
DC-Energy Storage	Inductive, Dynamic	Capacitive, Static

Figure 5. Voltage-Fed Power Supply Driving a Series-Resonant Furnace Circuit
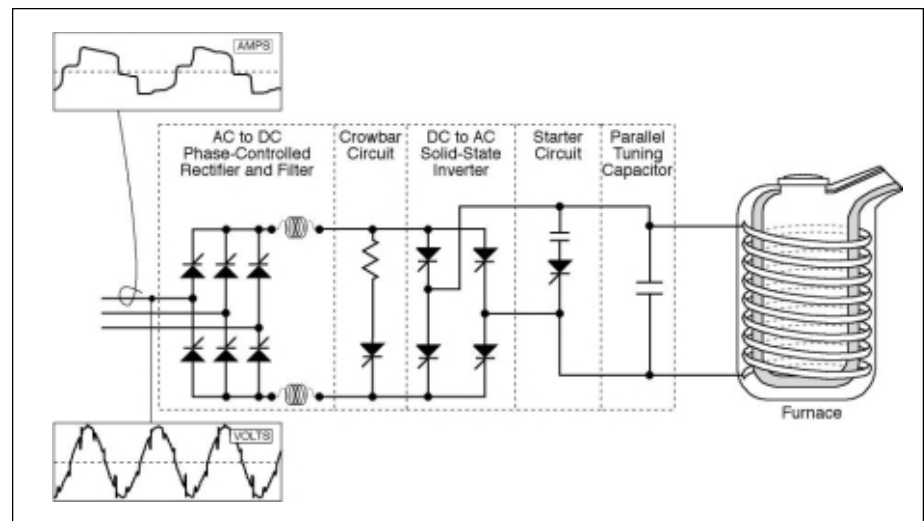

Figure 6. Current-Fed Power Supply Driving a Parallel-Resonant Furnace Circuit

furnace current than the voltage-fed power supply.

One side effect of using a phase-controlled rectifier in the current-fed power supply is voltage notching. The line voltage is notched because a momentary line-to-line fault occurs as each phase rectifier device is turned on before the other phase device has commutated off. Depth of the notch depends on the circuit impedance between

furnace transformer and the rectifier. Width depends on the timing between turn-on and turn-off. Notches are more severe near the converter, as illustrated in the voltage waveform shown in Figure 6. Notching can cause equipment operating problems when propagated in a plant electrical system. The most common problem caused by notching is tripping of other power supplies and DC drives.

3

Common Power Quality Concerns About Induction Furnaces

Sometimes thought to be a panacea for the induction melting process, modern solid-state power supplies have actually been a mixed blessing for achieving compatibility with the electric utility system. Large three-phase power supplies for furnaces, while providing economies of scale with higher productions levels, also bring large fluctuating load currents with varying levels of harmonic distortion. These varying furnace currents can affect distribution line-voltage regulation and quality. Table 2 provides a summary and comparison of power quality concerns for both the current- and the voltage-fed power supply.

Generation of Current Harmonics

Both current- and voltage-fed inverters generate harmonics back into power lines in the process of rectifying AC to DC. In the larger furnaces, it is popular to provide more than one rectifier bridge, along with phase-shifting transformers. This reduces the amount of current per bridge and the level of harmonics in the combined current drawn from the utility. Each three-phase bridge requires six devices, and one positive and one negative pole for each phase. A single bridge, such as shown in Figures 5 and 6, is called a six-pulse rectifier, two bridges a 12-pulse, as shown in Figure 7, and so on.

Increasing the number of rectifier bridges adds more steps in the waveform of the line current, making it more sinusoidal. The harmonics produced by 6-, 12-, and 24-pulse rectifiers are shown in Table 3. Assuming and ideal square wave, a rectifier should only have harmonics that are an integer multiple of the number of pulses ±1. For example, in a 12-pulse rectifier, the harmonic components should be 11, 13, 23, 25, and so on. However,

Table 2. Power Quality Comparisons (Single-Rectifier-Bridge Configuration)

Characteristics	Current-Fed Inverter	Voltage-Fed Inverter
Line-Voltage Notching	Yes (Caused by Phase Control)	No
Harmonic Generation	High	Moderate
System Power Factor	0.7-0.95 (Depends on Phase Control)	0.95
Generates Inter-Harmonics	Yes (Depends on Furnace Frequency)	No

Table 3. Ideal Square Wave and Practical Harmonic Spectrum for Furnace Rectifiers

Rectifier	Individual Harmonic Order and Levels (% of Fundamental)								
Harmonic→	5th	7th	11th	13th	17th	19th	23rd	25th	Total
6-Pulse (I)	20	14.3	9.1	7.7	5.9	0.5	4.3	4.0	29%
6-Pulse (P)	17.5	11.0	4.5	2.9	1.5	1	0.9	0.8	21.5%
12-Pulse (I)	0	0	9.1	7.7	0	0	4.3	4.0	15.5%
12-Pulse (P)	2.6	1.6	7.9	5.5	0.2	0.1	2.3	0.8	10.4%
24-Pulse (I)	0	0	0	0	0	0	4.3	4.0	5.9%
24-Pulse (P)	2.6	1.6	0.7	0.4	0.2	0.1	1.9	0.8	3.8%

I = Ideal Square Wave

P = Practical Case

due to unbalances, other harmonics are present in practical applications, as shown in Table 3. Even so, the total harmonics in most practical applications are moderately less than theory predicts for ideal square-stepped waveforms where each individual harmonic (N) is 1/N of the fundamental.

Figure 7. Typical 12-Pulse Bridge Rectifier Configuration with Phase-Shifting Transformers

Power Factor of Furnace and Power Supply

The term "power factor" is well defined for 60-Hz systems as the phase difference between the fundamental current and voltage. In the presence of harmonics, power factor is best defined as the ratio of the watts over the total kVA for all frequencies. Distorted systems have limited power factors even when the fundamental voltage and current are in phase. For example, when the current is 21.5% distorted, as with the practical case of a six-pulse rectifier, the maximum power factor is 0.98 instead of 1.0. At 60% distortion, the maximum power factor is about 0.86. The expected power factors for 6-, 12-, and 24-pulse bridge rectifiers in full-wave rectification mode are relatively high, as shown in
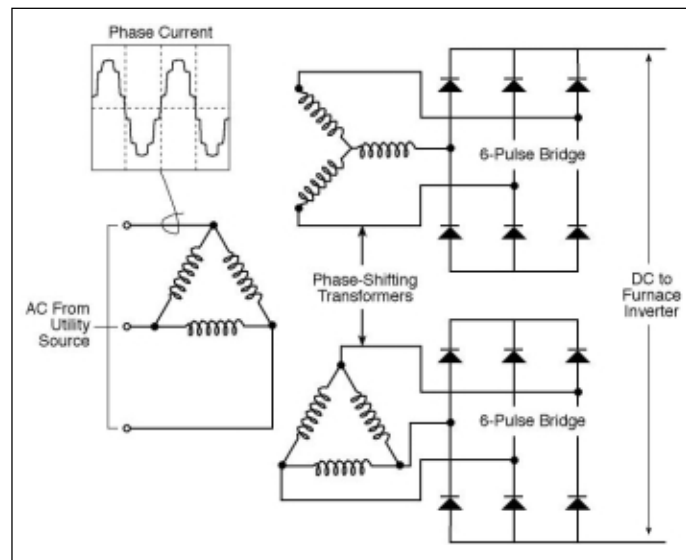
Table 4. The greater the number of pulses the greater the expected power factor. Compared to the full-wave rectifier in voltage-fed power supplies, the phase-controlled rectifier in current-fed power supplies uses a delay in turning on switches to control power levels and to regulate the DC bus voltage. It should be noted that the power level and power factor in a phase-controlled rectifier drops rapidly with the increase of delay angle. At a delay angle of 30°, the maximum is 0.95, at 90° it is less than 0.7, and at 120° it drops to 0.46. Therefore, if the power supply is current-fed, low power factors can be expected when the power supply reduces power to the furnace.

Table 4. Expected Power Factor for Full-Wave Rectifiers

Number of Pulses	Power Factor
6	0.955
12	0.988
24	0.997

Voltage Fluctuations Caused by the Furnace Circuit

In addition to the harmonics that are normally expected from different pulse rectifiers large furnaces operating at a few hundred hertz can generate significant non-characteristic harmonics. These harmonics, which fluctuate with the frequency of the furnace resonant circuit, are usually not multiples of the supply frequency, making them difficult to filter. This phenomenon, known as inter-harmonics, can overload power system capacitors, introduce noise into transformers, cause lights to flicker, instigate UPS alarms, and trip adjustable-speed drives (see "Inter-Harmonics in Power Systems").

The typical scenario for the generation of inter-harmonics is a relatively large furnace with a current-fed power supply operating between 100 and 500 Hz on a distribution feeder. When the power supply inverter is operating at frequency f_0, the frequency reflected back to the rectifier is two times f_0. This frequency combines with the line frequency (60 Hz), resulting in line currents containing harmonics of two times f_0 ±60, $4f_0$ ±60,

and so on. For example, a 12-pulse rectifier feeding a furnace operating at 123 Hz may have inter-harmonics at 186 and 306 Hz, 432 and 552 Hz, and so on. These frequencies are not characteristic of the 12-pulse rectifier and are fed back into the power system from the current of the furnace's resonant circuit.

When inter-harmonics combine with the fundamental voltage, modulations of the power system voltage may interact with other equipment. Light flicker is probably the most common interaction problem. Many utilities have dealt with electric arc furnaces as a large-scale cause of flickering lights. Induction melting can also cause annoying lamp flicker. However, the mechanism is related to voltage fluctuations resulting from inter-harmonic currents rather than from arcing currents. Figure 8 shows the fundamental 60-Hz voltage with amplitude modulation of approximately 6 Hz, resulting from a 186 Hz inter-harmonic. This voltage causes a strong light flicker in most lamps.

The interaction level depends on the relative size of the furnace, its operating frequency, and loading. Also, the effect might be aggravated by resonance in the system, which causes amplification of the inter-harmonic frequencies at certain points in the power system. New IEEE/

IEC standards in flicker prediction, measurement, and assessment can be a big help in dealing with light flicker caused by the operation of induction furnaces (see "Standards for Assessment of Voltage Fluctuations and Lamp Flicker").

Solutions to Induction Furnace Power Quality Problems

When an induction furnace is causing power quality problems, other customers are often involved. Both end user and power provider want to consider all practical solutions. Tools for avoiding and resolving typical problems include measurement and assessment methods, application of standards, changes in the furnace or utility power supply, special operating procedures, and power conditioning. Pre-installation planning and post-installation problem-solving for a
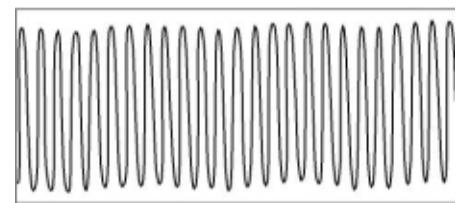

Figure 8. System Voltage Modulated by 186-Hz Components

Inter-Harmonics in Power Systems

Inter-harmonic is a relatively new classification of power system distortion. Its effect on the power system is unique, as are the methods for measuring inter-harmonics and mitigating its effects. Inter-harmonics can be thought of as voltage or current components that are not related to fundamental frequency or to integer-harmonic components of the system. As furnace power supplies become more sophisticated, the frequencies of the current they draw are less likely to be limited to harmonics of the fundamental.

The equipment that causes inter-harmonics includes induction furnaces, static-frequency converters, cycloconverters, induction motors that drive shakers, and DC arc furnaces. Generally, any equipment that draws a load current that pulsates asynchronously with the fundamental power system frequency generates inter-harmonics. In the case of induction melting, the variable frequency of the furnace is likely to cause inter-harmonics in the power system. The typical impacts on other equipment are flickering lights or computer screens, tripping of certain power electronic equipment, and heating in the power system similar to the heating caused by harmonic currents.

Standards are still emerging on this subject. IEEE 519-1992 indirectly addresses inter-harmonics in the discussion on cycloconverters. A future IEEE standard is expected to provide general technical descriptions of the phenomenon, methods of measurement, and guidelines for limits. The IEC 61000-2-1 currently defines the inter-harmonic environment, and IEC 61000-4-7 describes a measurement technique. Even with these standards, agreement among popular harmonic monitors does not exist. If a monitor can detect inter-harmonics, the most common result is an under-registration of the inter-harmonic levels.

specific foundry case will demonstrate options for preventing and resolving power quality problems.

Pre-installation planning usually starts with an assessment of the relative size of the end user compared to the utility power source. Consider the installation of a 2-MW furnace in a foundry on a 12-kV distribution feeder. Concerns are harmonic generation, light flicker, and interaction with other equipment at the foundry. The first step is to establish a point of common coupling and calculate a short-circuit ratio (SCR) of available short-circuit power (SSC) divided by average maximum demand power. Figure 9 illustrates this calculation for a foundry that has an SCR of 25.8 at the point of common coupling with the distribution system.

Options to Control Furnace Harmonics and Power Factor

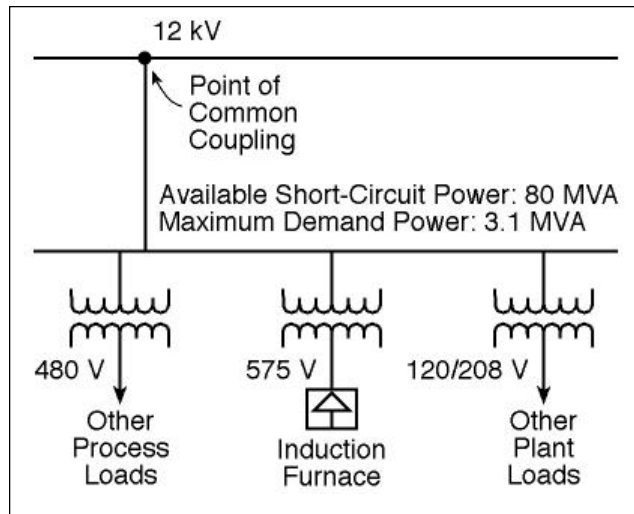IEEE Standard 519 provides recommended harmonic distortion limits

Figure 9. Induction Furnace Point of Common Coupling Showing Relative Size with Power System (Max. DemandAVE =3.1 MVA, SCR = 80/3.1 = 25.8)

for both end-user current and power-supplier voltage. The current limits depend on the relative size of the plant or its SCR. Current limits in 519 are calibrated for the harmonic spectrum of a six-pulse-rectifier. These current limits will relax if the rectifier is a higher pulse number. Limits are given for both total

demand distortion (TDD) and individual harmonic distortion. In most practical cases, these individual harmonic limits are the most restrictive.

For example, assuming there are no power-factor-correction capacitor banks at the foundry, all the harmonic currents from the furnace are likely to flow into the utility distribution system. At the point of common coupling (PCC), given a short circuit ratio of 25.8, the total demand distortion limit in IEEE 519 is 8%, and the individual single harmonic limit will depend on the rectifier type. With this information, the following procedure can be used to determine the maximum furnace size at the location:

1. Identify the harmonic spectrum of the particular furnace to be connected. This will depend primarily on the furnace rectifier type and the supply

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Standards for Assessing Voltage Fluctuations and Lamp Flicker

Annoying lamp flicker can occur when rapid changes in load current cause the power system voltage to fluctuate. Both incandescent and fluorescent lamps can flicker during voltage fluctuations. The standards for measuring and limiting lamp flicker are based on the 60-W incandescent lamp.

Assessing whether or not voltage fluctuations might result in observable flicker can be done using a flickermeter calibrated for a typical lamp and human eye-brain response. The best methods for this measurement were developed in Europe for 230-V incandescent lamps and are contained in standards published by the International Electrotechnical Commission (IEC). These standards were recently adapted for 120-V lamps used in North America. In 1999, the Institute of Electrical and Electronics Engineers (IEEE) accepted the IEC method and will publish it as IEEE Standard 1354. As shown in the figure, the flicker thresholds in this new standard are similar to flicker curves based on the early General Electric studies conducted in the US in the 1920s. The difference between the new standard and the IEEE flicker curves is that a measurement method is also specified in the new standard.

In the IEC method, the threshold of irritation is defined as Pst=1, based on 60-W incandescent lamps and a short-term (10-minute) measurement period. For a long-term (two-hour) measurement period, a Plt is defined as the cube root of 12 successive Pst measurements averaged. The allowed percent of voltage change for Pst = 1 varies with the frequency of voltage fluctuations. For example, at 120 changes per minute (two changes per second), the IEC curve indicates that irritating flicker will result from voltage fluctuations that are about 0.8 percent or more of the nominal voltage. At that same frequency, the original IEEE curves give a similar result of about 0.7 percent. Because IEEE had no standard way to measure flicker, the IEC flicker standards have been adopted.

Three IEC standards may help in resolving a flicker dispute. Limits on voltage fluctuation for equipment greater than 16 amps are provided in IEC 61000-3-5. Methods for assessing fluctuating loads at medium and high voltage are covered in IEC 61000-3-7. Flicker measurement is specified in IEC 61000-4-15. The same measurement method is now also included in IEEE Standard 1354.

Voltage Fluctuations That Cause Irritating Flicker (IEC 6100-4-15)
Voltage Fluctuations That Cause Irritating Flicker (IEEE 141 and 519)
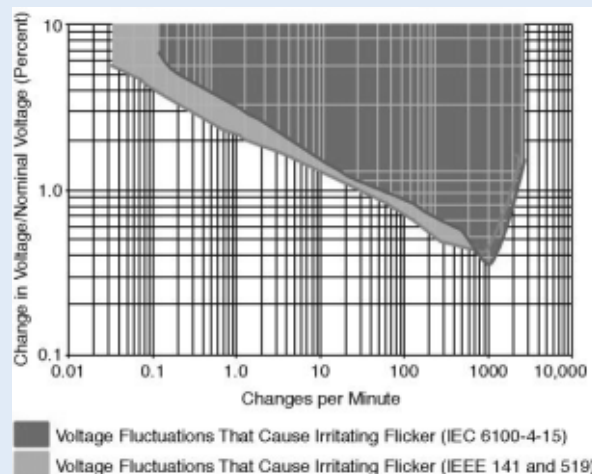
strength. The furnace manufacturer should have a good estimate. For this example, use the spectrum given in Table 3.

2. Determine the IEEE 519 individual harmonic distortion limit that will apply to this furnace configuration. For a basic six-pulse rectifier, the 5th is the largest individual harmonic, and the IEEE limit for the 5th is 7%. When multi-bridge furnace rectifiers such as 12- or 24-pulse are used, the largest single harmonic will change from the 5th to 11th and 23rd. In these cases, the limits in IEEE 519 need to be multiplied by the square root of the pulse number and then divided by 6. For example, if the rectifier is 12-pulse, then the limiting harmonic is the 11th and the IEEE limit for an SCR of 25.8 is 3.5% times $\sqrt{12/6}$ or $\sqrt{2}$. So the limit 11th is 3.5% x 1.41 = 4.9%.

3. Compare estimated percent distortion with the IEEE allowed distortion percent for the limiting individual harmonic. The relative size of the furnace allowed is a simple ratio of the allowed percent distortion divided by the expected percent. Assuming an ideal square wave, where the 5th is 1/N or 20%, the maximum furnace size from Table 3 is 0.07/0.2 or 35%. In the more practical case, the 5th is expected to be 17.5% and the maximum furnace size is 0.07/0.175 or 40% of 3.1 MW.

This method demonstrates that for practical cases, the allowed furnace size increases as the pulse number of the power supply increases. Figure 10 illustrates the IEEE 519 recommended limit for the relative size of the furnace based on individual harmonic levels from Table 3. Another rule of thumb sometimes used is that furnaces greater than 2 MW should be 12-pulse, and furnaces greater than 10 MW should be 24-pulse.

Sometimes the actual furnace harmonics are higher than predicted because of insufficient series reactance, unbalance loading, or resonance with other power system filters and equipment. When IEEE limits are violated, some form of series-balancing reactor or parallel-tuned filter may be required. Consult the furnace manufacturer to determine if changes to the furnace are practical. If harmonic frequencies are changing during furnace operation, an on-site filter may be very difficult to apply. In nearly every case, a study is needed to select the best solution for the application.

Options to Control Furnace-Related Light Flicker

Predicting Flicker Complaints
The first step in assessing furnace-related light flicker is to monitor furnace operation and voltage fluctuations simultaneously. Flickermeters calibrated for 120-V lamps are available. Measurements can be quite effective in predicting flicker complaints,

even when voltage fluctuations are caused by inter-harmonics. By comparing the flicker levels with the furnace operating mode, useful correlations may be obtained. When attempting to reduce flicker levels, the meter will provide quick feedback following changes in the power system configuration, the furnace operation, or the PCC. Measurements before and after furnace installation are usually helpful in diagnosing and correcting flicker problems.

Several standard assessment methods are available for use prior to furnace installation. Use a short-circuit ratio test for initial screening where flicker problems are not expected. This assessment is simply based on the ratio of the power change, ΔS, divided by the available short circuit power, S_{SC}, at the PCC. The limits to be applied for "automatic acceptance" of the fluctuating furnace load also depend on frequency of load changes, Cf, as shown in Table 5. Note that this simple method is not effective in cases where either ΔS or C_f are not predictable. Inter-harmonics introduced into the power system from the furnace resonant circuit may be one of these unpredictable cases.

Table 5. Maximum Permissible Load Changes (Adapted from IEC 61000-3-7)

C_f (Changes/Minute)	$\Delta S/S_{SC}$ (%)
>200	0.1
10 to 200	0.2
<10	0.4

If the voltage waveform at the PCC can be described in a digital waveform, then a standard flickermeter simulation will give the expected Pst. When the general shape of the voltage fluctuation is known, IEC 61000-3-3 provides shape-factor charts to predict flicker levels after installation. In the simple case of rectangular voltage variations, with a known and a fixed frequency, the traditional flicker curve can be used to predict complaints. Table 6 summarizes available assessment methods.

Existing Flicker Problems
When the installed furnace is already causing flicker complaints, the most likely source is inter-harmonics. Experience has shown that the current-fed converter, without sufficient filtering, promotes the
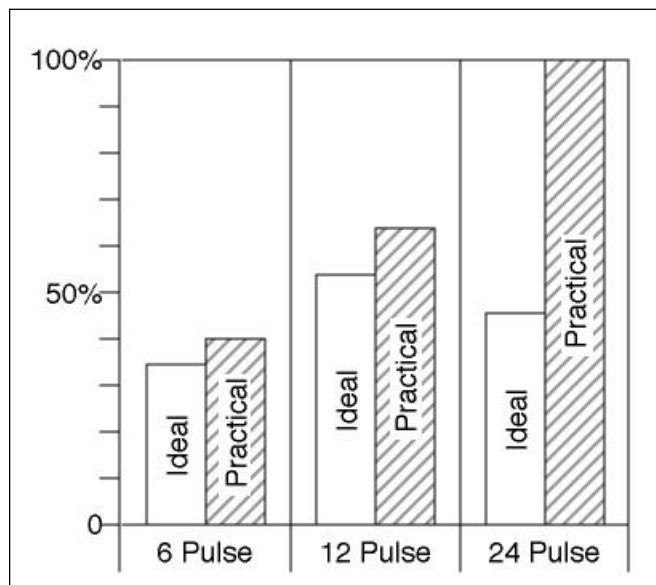

Figure 10. Limits on Furnace Size as a Percent of Plant Load for Ideal and Practical Conditions

Table 6. Methods for Predicting Load-Related Flicker Complaints (Pst or Plt)

Type of Voltage Change Data	Assessment Method	Standard Reference
Actual Load Operating	Flickermeter	IEEE 1354, IEC 61000-4-1
Predicted kVA Change	Short-Circuit Ratio Test	IEC 61000-3-7
Digitized Waveforms of Change	Flickermeter Simulation	IEC 61000-4-15
Typical Shape of Voltage Change	Standard IEC "Shape Factors"	IEC 61000-3-3
Rectangular Change, Fixed Rate	Traditional Flicker Curve (Pst=1)	IEEE 1354, IEC 61000-3-3

interaction of furnace and power-line frequencies to cause voltage fluctuations.

Adding series inductance inside the furnace power supply at the DC link or adding parallel capacitance on the power line may reduce the flicker. The inductors will also reduce the propagation of notching. However, side effects such as reduced voltage at the furnace and overvoltage at the plant bus must also be considered. Flagging specific troublesome operating levels or frequencies and controlling the furnace to avoid these operating points can be an effective way to mitigate inter-harmonic interactions. Less desirable measures include restricting operation to only certain hours during the day, increasing the service capacity, or requiring reconfiguration of the distribution feeder to reduce interactions.

In some cases, a Pst level close to unity may still result in isolated flicker complaints. Most likely these flickering lamps are more affected by voltage fluctuations than the standard 60-W incandescent. Some fluorescents, particularly compacts, and low-wattage or dimmed incandescent lamps are very prone to flicker. Also some people are more sensitive to light changes than average. In these cases, correction at point of complaint, such as changing the lamps or adding a fast voltage regulator, may be cost-effective.

Topics for Future Investigation

Active control of the furnace frequency and power to avoid adverse interactions with the utility may be effective in maintaining a compatible interface between furnaces and utility service. The impact of utility voltage sags, momentary interruptions, and switching transients is gaining importance as furnaces become more sophisticated with sensitive process controls. Improved inter-harmonic measurement and elimination methods are needed as more melting is carried out by induction.

Other Resources

TechCommentary Induction Melting, CMP-72, 11/91

- CMP *TechApplications*
  - Induction Melting for a Competitive Advantage, CMP-048, 2/90
  - Induction Melting for Higher Productivity, CMP-1188-018
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